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An integrated methodology for flexible aircraft control design
Une méthodologie globale de conception de lois de commande pour l'avion souple

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Abstract

This article details recent research activities of the *Systems Control and Flight Dynamics* department of ONERA in the field of flexible aircraft control. A long-term research program has been conducted for several years, with governmental funds, and with the technical support of AEROSPATIALE-Avions (Toulouse, France). Beyond the primary objectives of achieving various specifications for simultaneous aircraft motion and structural dynamics control, more fundamental questions are addressed, concerning the implications of rigid-structural dynamics coupling for the selection of suitable control law design methodologies.

Résumé

Cet article détaille les recherches récentes menées dans le domaine de la commande de l'avion souple au département de *Commande des Systèmes et Dynamique du Vol* de l'ONERA. Un programme de recherche d'envergure sur plusieurs années a été financé par le gouvernement français avec le soutien technique d'AEROSPATIALE-Avions (Toulouse, France). Au delà de la prise en compte des diverses spécifications relatives à la commande simultanée des dynamiques du vol et de la structure de l'avion, on aborde des questions plus fondamentales relatives à l'impact des couplages rigide-souple sur les méthodes de conception de lois de commande.

1 Introduction

For most aircraft of the past and present generations, control of the rigid and structural dynamics are considered as two distinct problems, as far as the frequencies of the structural modes do not overlap the frequency range of the rigid flight control. Generally, the rigid control is designed first, with low pass filtering of the outputs to avoid residual coupling with the structure, using a *passive control strategy* which leads to poor performance in perturbation rejection. Additionally, structural dynamics can be controlled using a specific feedback loop with appropriate filtering. This gives reasonably good results as long as the frequency separation assumption between rigid and flexible dynamics is valid. This is not any more the case for new generations of large transport [15] or supersonic aircraft [30] for which first structural modes show low frequencies and remain excited by the rigid control [4]. Filtering of measurements has limitations [10,11], generally leading to a loss of performance for the rigid dynamics, and unacceptable flight qualities. Control of such aircraft becomes a global rigid and flexible problem, and control laws must be designed in a global one-step procedure leading to a unique control loop with complex multivariable controllers [3]. First published developments in this research area of simultaneous rigid and flexible control are recent [5,6]. Some methodologies already have been proposed for civil aircraft applications [7,9,12,22]. As required performances on structural dynamics are very ambitious, an *active control strategy* is necessary. This is a real challenge, since the system model is of high order and subject to many uncertainties or unmeasured parameter variations against which the control laws must be robust. This article details a global methodology [34], developed in a long term research program COVAS[1] which has been conducted for several years, in the System Control and Flight Dynamics department of ONERA, as a solution for the flexible aircraft control problem. This research was funded by Direction des Programmes de l'Aviation Civile, via Service des Programmes Aéronautiques, with the technical support of AEROSPATIALE-Avions.

[1]COntrôle du Vol de l'Avion Souple, Flexible Aircraft Flight Control

Paper presented at the RTO AVT Specialists' Meeting on "Structural Aspects of Flexible Aircraft Control", held in Ottawa, Canada, 18-20 October 1999, and published in RTO MP-36.

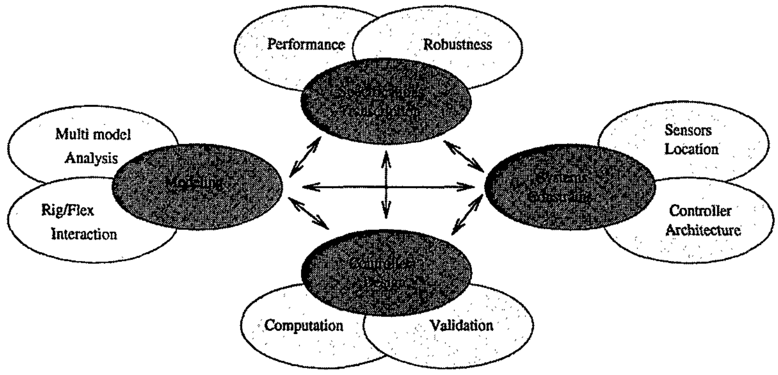

Figure 1: Related sub-problems for flexible aircraft control design

2 A multiobjective problem

Flexible aircraft control design is very challenging, because many issues are concerned as illustrated in figure 1. Most include considerations about rigid-structural interactions. This makes flexible aircraft control a multiobjective problem where different trades off are necessary.

2.1 Heterogeneous specifications

The selection of a methodology for solving this problem from the engineering point of view is strongly connected to the nature and the requirements of the control specifications. As summarized in table 1, specifications are heterogeneous, expressed either in time, frequency or parameter domain. The candidate design methodology must be able to simultaneously achieve these various specifications, for both rigid and structural dynamics.

Specs	Rigid	Flexible
Perf.	Time	Frequency
Robust.	Parameter	Frequency/Parameter

Table 1: Nature of control specifications.

Performance specifications: time and frequency domain

Performance specifications for the rigid dynamics are derived from required flight qualities and expressed in the time domain. These are settling times and decoupling constraints on the rigid states of the aircraft. The most natural control approach for achieving these specifications is eigenstructure assignment, which has proved efficiency for rigid aircraft [1,2]. However, applying this technique in its basic formulation to flexible aircraft leads to unacceptable coupling effects with the structure [22].

Performance specifications for the structural dynamics are mainly related to gust alleviation for load minimization and passenger comfort increasing [33], so that an active control strategy becomes necessary. These specifications are expressed in the frequency domain in terms of attenuation for acceleration responses to turbulence. Two competitive strategies are possible. The most natural one is explicit optimal control [23], trying to minimize the turbulence-to-acceleration transfer function in the frequency bandwidth where performance is needed. The second one is more physical. It consists in damping augmentation for modes that are the most significant for performance [22,24,25]. These two strategies have similar interpretations in terms of performance for high requirements in active control of the structure. It can be shown that optimal control naturally increases damping ratios, and that damping augmentation strategies can be interpreted in an optimal control scheme.

An additional specification is expressed in the frequency domain, namely the avoidance of pilot to structure coupling over a larger frequency domain than for rigid aircraft.

Robustness specifications: frequency and parameter domain

Standard robustness requirements for the rigid control are expressed in the parameter domain (robustness against aerodynamic coefficients variations, delays in the measurement or actuation loops, ...).

There are specific robustness specifications related to the structural dynamics. First, the model of the flexible aircraft is not so well known as the rigid model [8]. Highest frequency modes are generally neglected during modeling (normally called dynamical uncertainties), so that the control law must introduce convenient roll off. Moreover, there are several unmeasured parameters (mass, fuel distribu-

tion in the tanks, ...) in the flexible structure model parameters, leading to uncertainties against which the control law must be robust. This has motivated lots of research in the field of robustness analysis [16,17] and robust synthesis [18].

2.2 Systems constraints

Beyond the achievement of these primary objectives, the designed controllers should be easily adaptable to changes in the specifications and tuneable for refinements after flight tests. The control design methodology must provide a few *high level tuning parameter* with physical interpretation, and support some constraints for implementation considerations.

Low order control design for high order dynamics

As high performance is expected for structural control, a complex modeling of the dynamics is necessary (typically 50 to 80 states), which may lead to high order multivariable controller and violate order constraints related to real time implementation, and controller readability for adjustment during flight tests. The controllers must be as simple as possible, with physical interpretation. There is a need for lower order controller design. Among all possible strategies illustrated figure 2, direct design is the most complex, as the equations for the computation of optimal solution are untractable [20]. Multimodel modal control with a priori fixed controller dynamics gives a solution [22,31]. Alternatively, a low order model can be computed before control design. Model reduction is rather difficult, as the best reduction model for control design depends on the controller that is not yet known when reduction is computed [19,26]. The last strategy consists in computing a high order controller first, which may be difficult for high order model but guarantees a full information control design, and then reducing it, trying to recover known closed loop performance. However, reduction involves mathematical manipulations that may lead to unreadable multivariable controllers.

Sensors

Obviously, the more sensors are used in the control architecture, the better performance can be expected. However, for some practical reason related to implementation, particularly for redundancy [2], the amount of sensors should be strictly limited, which may lead to restrictions in performance. For a given number of sensors, a tricky selection of their location must then be undertaken, in order to reach the best trade off in performance and robustness.

[2] this problem is not addressed here

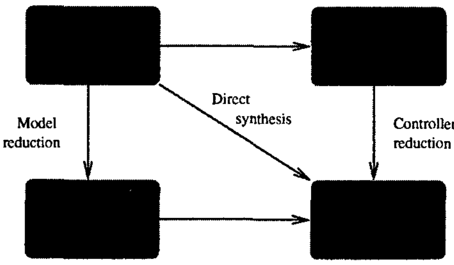

Figure 2: Strategies for low order controller design

3 Nominal model design and multimodel analysis

For rigid aircraft, control design can be performed chronologically within different steps: sensor selection, rigid control design, analysis of potential structural coupling, and structural filtering. As already mentioned, all steps must be considered in a one step control design for the flexible aircraft control case. However, for the sake of clarity, different levels of complexity are introduced in the sequel for presenting the methodology. They are illustrated in figure 3.

To complete the design process, various kinds of tools must be available: for selection of a convenient design model, for transcription of specifications, for computation of controllers, and for validation. Namely, the availability of multimodel analysis tools is a key point for having a good trade off in performance and robustness for flexible aircraft control laws.

3.1 Nominal model design with parameter uncertainty description

For controlling systems subject to parameter variations, multimodel control design techniques can be used [22] or other sophisticated techniques such as LPV (Linear Parameter Varying) [32] if an explicit description of parameter dependence is available. For flexible aircraft control, such a description of the structural dynamics is not always available. Modern control design techniques based on a single design model are used, with possible preliminary reduction to get a reasonable order, and less sophisticated description of parameter variations is used.

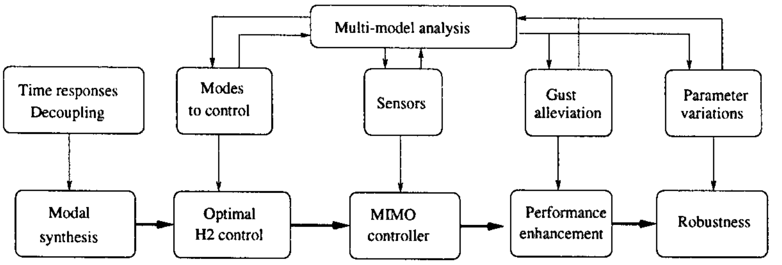

Figure 3: A strategy for flexible aircraft control design

Among strategies available for low order control design, a combination can be made between *preliminary open loop reduction* which brings the model to a reasonable order without removing any important information for control, and post synthesis *closed loop reduction*, keeping the least information for good control performance recovery on the true aircraft.

In the preliminary analysis of the control problem, multimodel analysis allows selection of a design model, and offers possible characterization of parameter variations on the structural modes in defining amplitudes of intervals in which parameters are expected to vary. This will be used for specifying robustness.

3.2 Generalized multimodel analysis

Indeed, multimodel analysis is useful for most control considerations, as illustrated in figure 3. It allows selection of modes to be controlled and sensors to retain for feedback. In the validation process of the control laws, it can detect *worst case* behaviors to be taken into account for performance and robustness improvement.

Selection of modes for active control

Modes to be controlled must be selected via a multimodel analysis of the open loop transfer from gust to acceleration, in order to achieve good robustness in gust alleviation performance, which is one of the most important control specification. An example is given figure 4 for the lateral dynamics of a conceptual aircraft, with analysis of transfer functions for different mass distribution configurations. A single model analysis would lead to forget some modes which are not significant for the corresponding configuration, but which should be retained as they significantly contribute to gust response for other configurations.

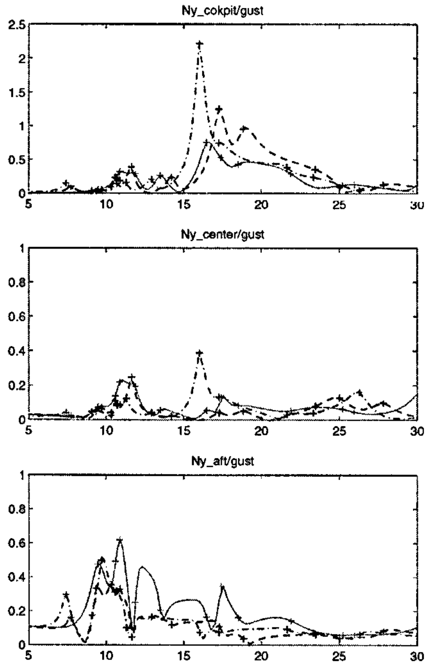

Figure 4: Multimodel analysis of modal contributions to gust response for selection of modes to be controlled

Selection of sensors

A major issue for control design is the capability of observing the dynamics of interest through the sensors. For rigid control purpose, sensors that are not polluted by the structural modes are generally preferred, in order to recover the best rigid performance and to limit the use of notch filtering. For high authority control of flexible structure, it becomes necessary to use outputs having a significant contribution from the structural modes to be controlled. As the modal contribution is very sensitive to measurement location, optimization of sensors location must be considered [13,14]. The selection of suitable sensors for control is also strongly dependent on the control objectives: sensors must be selected among those which contain the highest contribution of the structural modes to be controlled, but which are the least sensitive to variations on unmeasured parameters (especially mass distribution). For the lateral dynamics of a conceptual aircraft, figure 5 illustrates the energy of controlled structural modes which is contained in measurements at different locations along the fuselage, and a characterization of sensitivity to parameter variations. In this particular example, such an analysis would lead to select sensors ϕ and p at the center of the aircraft as at this location the highest energy and the smallest variations are obtained. On the contrary, sensors for N_y would be preferred at aft and those for r at front or aft.

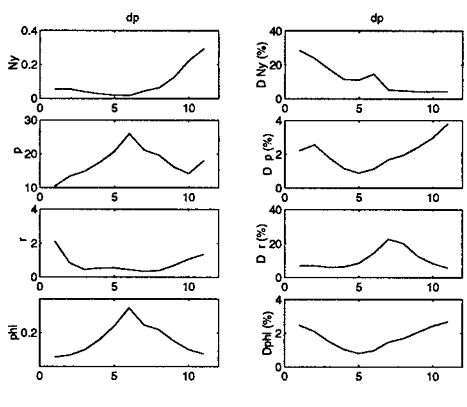

Figure 5: An illustration of sensors selection
Left: contribution of structural modes to output energy
Right: amplitude of variations due to parameter uncertainties
Sensor location: #1 cockpit, #6 center, #11 aft

4 Controller design

4.1 A generic architecture

A very generic controller architecture is used as shown figure 6, with feedforward H from pilot inputs to actuator signals which will include adequate filtering to prevent pilot/structure dynamical coupling, and with feedback K to control the closed loop dynamics and achieve perturbation rejection.

4.2 A standard formulation for transcription of specifications

The selected control design technique must allow simultaneous transcription of specifications of heterogeneous nature and the computation of the controller in one-step. For this, a convenient tool is the standard form of figure 7. First introduced by Doyle [21] in the context of robust control design, this formalism is now used for many applications. It uses an input to output linear representation of the nominal aircraft dynamics that is artificially augmented for transcription of dynamical specifications, with extensions for description of parameter uncertainties such as in 3.1. This leads to an augmented system, connecting generalized inputs to outputs and defining a mixed performance/robustness index. The control problem is now to design a feedback controller between measurements y and control signals u sent to the actuators, for minimizing the energy transmitted in closed loop from perturbations e on the aircraft, to regulated variables z. The control design technique must be suitable for robust stabilization of the aircraft, i.e. achieving specified performance of the nominal dynamics subject to all perturbations specified in the standard form.

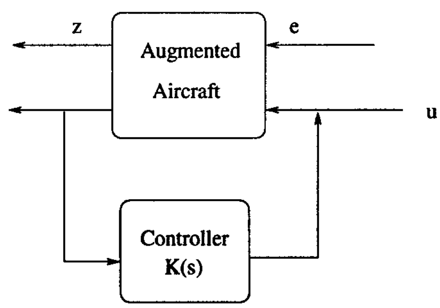

Figure 7: A general standard form for transcription of specifications

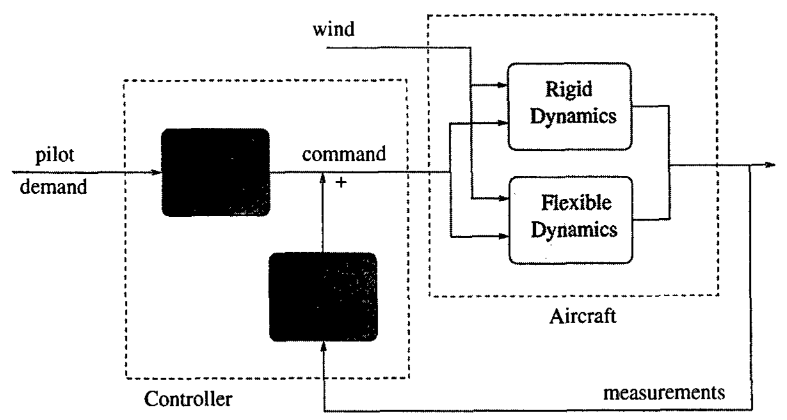

Figure 6: A generic architecture

4.3 High level tuning parameters

Figure 8 shows more details on a standard form that is used for flexible aircraft control. There are only a few blocks, for transcription of specifications, including both rigid and flexible control, roll off at higher frequencies (robustness against unmodelled dynamics), and for robustness against parameter variations using a perturbation approach. All these blocks only include a few adjustable parameters, which enables easy tuning of performance and robustness trade off. Such a standard form can be sophisticated for introducing more detailed specifications. Particularly, the nominal case description of the aircraft in figure 7 can be replaced by a more sophisticated modeling, using a specific block Δ for explicit dependence versus parameter variations, and another block $\Delta(s)$ for dynamical considerations, leading to an augmented description of the aircraft called LFT (Linear Fractional Transformation) illustrated figure 9.

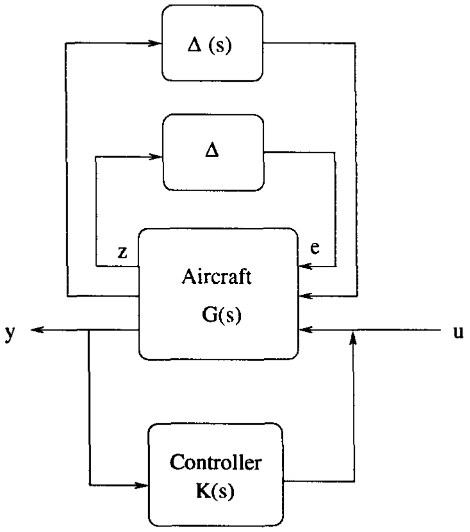

Figure 9: A generic LFT description for flexible aircraft control

4.4 Controller interpretation

The standard form naturally leads to optimal control (typically H_2 or H_∞), for minimizing the transfer functions between perturbations e and regulated outputs z, simultaneously achieving specified performance and robustness for rigid and structural control. As all blocks use input to output linear representations, the standard form and the associated optimal control design techniques are universal and remain useful for any order of the aircraft model. Only the parameter variation description block uses a specific state space representation of the aircraft.

Actually, H_2 is a generalization of optimal LQG control. Obtained controllers can be reformulated under an LQG like form, with state feedback and dynamical state estimation [27]. This justifies the transcription of parameter robustness specifications via a perturbation approach, using LTR and PRLQG extensions of LQG [28,29] in figure 8. Moreover, this interpretation leads to two-degrees-of-freedom controllers with feedback K and feedforward H in figure 6 having common dynamics. Figure 10 shows the transfer functions of the feedforward terms from pilot demand to actuator signals. It is clear that the dynamics lead to natural filtering of the pilot demand in order to avoid structural excitation and potential coupling. Feedforward can be improved via optimization within a multimodel framework.

4.5 Robustness assessment

Using the LFT description of nominal model with parameter variations such as in figure 9, robustness can be evaluated, using sophisticated analysis tools such as μ-analysis [35]. Analysing robustness in stability allows the computation of the parameter variations that can be supported bu the controller without destabilization of the closed loop. Analysing robust-

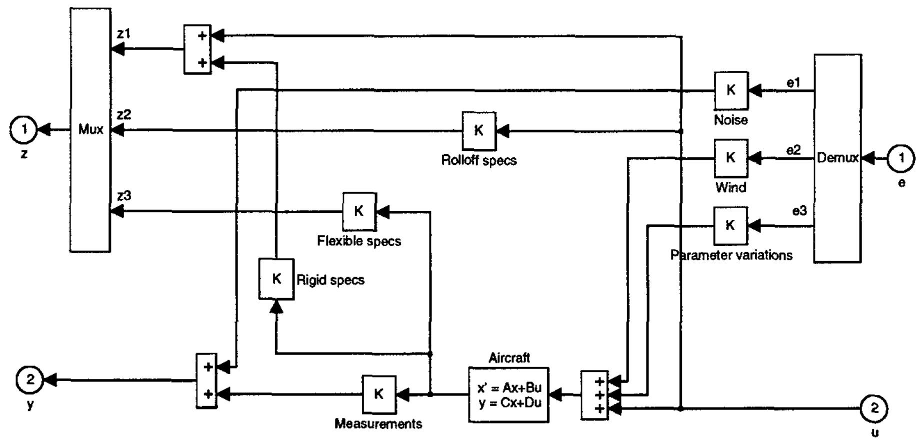

Figure 8: A specialized standard form for transcription of flexible aircraft control specifications

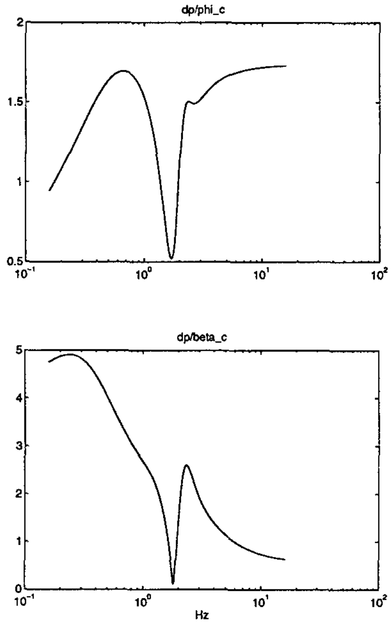

Figure 10: Dynamical feedforward

ness in performance indicates how closed loop rigid and flexible performance are modified by these parameter variations. There are difficult steps in this analysis. The first one is the construction of the LFT form. The second one is the computation of the μ norm [36], which can only be bounded. This is a difficult task for flexible aircraft having high order dynamics, with lowly damped modes.

5 Illustration for a conceptual flexible aircraft

The illustrative example is the lateral dynamics of a conceptual highly flexible aircraft, for which preliminary results have already been shown. All rigid and flexible specifications in performance and robustness have been transcribed into the formalism of the standard form, as shown figure 8. The control design technique is based on H_2. Though the dynamics of the aircraft is of very high order (about 80 states), the obtained controller is of low order (14 states), thanks to reduction. We now give a few more closed loop results, illustrated on next figures:

- Figure 11 shows time responses to standard demands in sideslip and roll, with a good robustness against large parameter variations on the rigid and flexible dynamics, and with low residual excitation of the structural modes.
- Figure 12 shows the frequency responses between gust and accelerations at various locations on the fuselage (front, center and aft) without and with active control of the structural dynamics. The achieved performance is about 50% reduction for all modal contributions below 3Hz.
- Figure 13 shows how pilot coupling transfer is

minimized in closed loop below 3Hz.

- Figure 14 illustrrates the analysis of robustness against uncertainties on flexible mode frequencies, using LFT representation and μ-analysis.

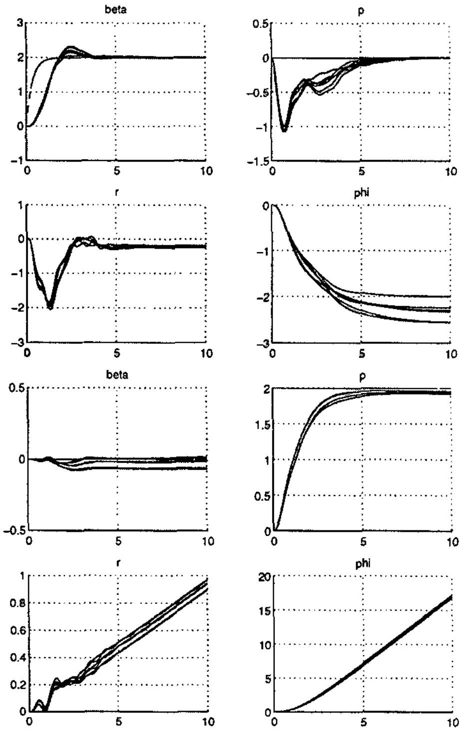

Figure 11: Illustration of robust performance for pilot demand in the time domain
Plots for 6 different mass distributions, light to heavy aircraft
Top 4 plots: 2^o sideslip demand with coordinated roll
Bottom 4 plots: $2^o/s$ roll rate demand with sideslip decoupling

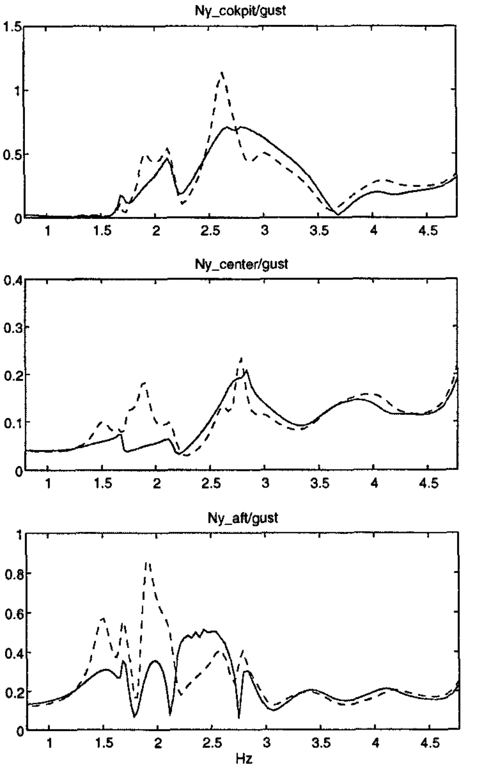

Figure 12: Illustration of gust alleviation performance in the frequency domain
Plots of lateral acceleration at various location along the fuselage:
- - open loop (no control),
- closed loop with active control

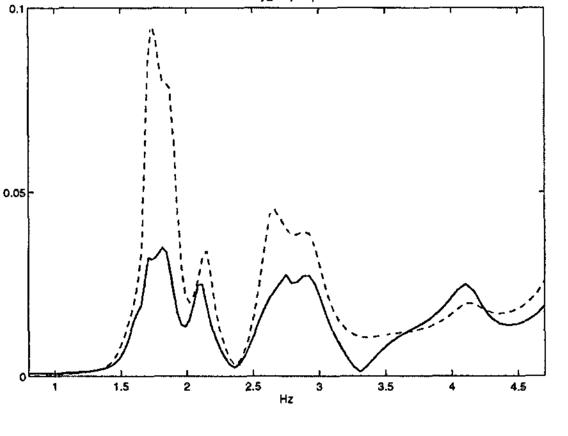

Figure 13: Minimization of pilot coupling transfer:
- - open loop (no control),
- closed loop with active control

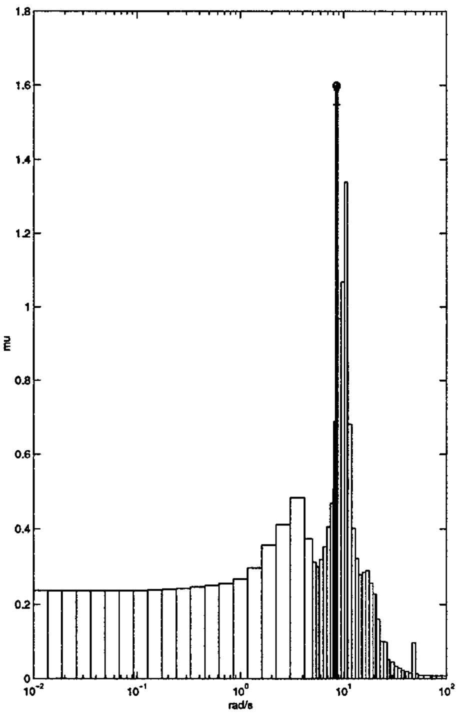

Figure 14: An example of robustness analysis using LFT representation and μ-analysis for uncertainties on flexible mode frequencies

6 Conclusion

As a result of the long-term research program COVAS in the Systems Control and Flight Dynamics department of ONERA, a methodology has been proposed and detailed in this article for flexible aircraft control. It is based on several sophisticated tools that allow:

- selection of a convenient design configuration, using multimodel analysis, and construction of a corresponding design model;
- transcription of heterogeneous specifications under a standard formulation, including standard rigid aircraft control performance specifications, more sophisticated specifications for active control of structural modes, and specifications for robustness;
- computation of controllers, using modern design and analysis techniques to achieve all rigid and flexible control specifications simultaneously ;
- validation and tuning of performance and robustness trade off, with very few *tuning parameters* for control optimization.

Research is under progress, in cooperation with AEROSPATIALE-avions, for modeling the explicit dependence of the aircraft dynamics versus structural parameters. This will allow enhancement in both performance and robustness, with possible introduction of parameter dependence in the structure of the controller.

References

[1] C. Favre, Fly-by-wire for commercial aircraft: the Airbus experience, Advances in aircraft flight control, Taylor and Francis, 1996

[2] J. Farineau, Lateral electric flight control laws of the A320 based upon eigenstructure assignment techniques, in Proceedings of the AIAA GNC conference, Boston, 1989

[3] J.M. Maciejowski, Multivariable feedback design, Electronic Systems Engineering Series, Addisson Wesley, 1989

[4] M.G. Gilbert, D.K. Schmidt and T.A.Weisshaar, Quadratic synthesis of integrated active control for an aeroelastic forward swept wing aircraft, Journal of Guidance Navigation and Control, 7-2, 1988

[5] M.G. Gilbert and D.K. Schmidt, Integrated structure/control law design by multilevel optimization, Journal of Guidance Navigation and Control, 14-5, 1991

[6] B. Newman and A. Kassem, Analytical relationships for linear quadratic aeroelastic flight control eigenvalues, Journal of Guidance Navigation and Control, 20-6, 1997

[7] F. Kubica, T. Livet, X. LeTron and A. Bucharles, Parameter robust flight control system for a flexible aircraft, Control Engineering Practice, 3-9, 1995

[8] K. Najmabadi, B. Fritchman and C. Tran, A process for model identification and validation of dynamical equations for a flexible aircraft, AGARD symposium on system identification for integrated development and flight testing, 1998

[9] I. Dardenne, Développement de méthodologies pour la synthèse de lois de commande d'un avion de transport souple, PhD thesis, SUPAERO, France, 1998

[10] S.Y. Chan, P.Y. Cheng and T. Myers, Advanced aeroservoelastic stabilization techniques for hypersonic flight vehicles, NASA Report 189702, 92

[11] B. Wie and K.W. Byun, New generalized structural filtering concept for active vibration control synthesis, Journal of Guidance Navigation and Control, 12-2, 1989

[12] F. Kubica and T. Livet, Flight control law synthesis for a flexible aircraft, In proceedings AIAA GNC conference, 1994

[13] W. Gawronski and K.B. Lim, Balanced actuator and sensor placement for flexible structures, In proceedings AIAA GNC, 1995

[14] B.S. Liebst, Accelerometer placement in active flutter suppression systems, Journal of Guidance Navigation and Control, 10-5, 1987

[15] J. Grouas, L'avion souple, Nouvelle Revue d'Aéronautique et d'Astronautique, 6, 1995

[16] D.K. Schmidt and B. Newman, Multivariable flight control synthesis and literal robustness analysis for an aeroelastic vehicle, In Proceeding AIAA GNC conference, 1990

[17] M.R. Anderson, Robustness evaluation of a flexible aircraft control system, In Proceeding AIAA GNC conference, 1990

[18] D.K. Schmidt and T.K. Chen, Frequency domain synthesis of a robust flutter suppression control law, Journal of Guidance Navigation and Control, 9-3, 1986

[19] S. Prudhomme, Reduction for aeroelastic aircraft control design: a practical approach, in Proceeding AIAA GNC conference, 1995

[20] D.C. Hyland and D.S. Bernstein, Explicit optimality conditions for fixed order dynamic compensation, in Proceedings IEEE Conference on Decision and Control, 1983

[21] J.C. Doyle, Analysis of feedback systems with structured uncertainties, in IEE Proceedings, part D, 129, 1982

[22] Y. Le Gorrec, Commande modale robuste et synthèse de gains autoséquencés, Approche multimodèle, PhD thesis, SUPAERO, France, 1998

[23] C. Hwang and W.S. Pi, Optimal control applied to aircraft flutter suppression, Journal of Guidance Navigation and Control, 7, 1984,

[24] W.E. Hopkins and J. Medanic and W.R. Perkins, Output feedback pole placement in the design of suboptimal linear quadratic, International Journal of Control, 34-3, 1981

[25] M.H. Amin, Optimal pole shifting for continuous multivariable linear systems, International Journal of Control, 41-3, 1985

[26] P.M.R. Wortelboer and O.H. Bosgra, Generalized frequency weighted balanced reduction, in Proceedings Conference on Decision and Control, 1992

[27] D. Alazard, P. Apkarian, Observer based structures of arbitrary compensators, International Journal of Robust and Nonlinear Control, 1999

[28] G. Stein and M. Athans, The LQG/LTR procedure for multivariable feedback control design , IEEE Transactions in Automatic Control, 32-2, 1987

[29] J. Douglas and M. Athans, Robust linear quadratic design with real parameter uncertainty, IEEE Transations on Automatic Control, 39-1, 1994

[30] D.K. Schmidt, Dynamics and control of hypersonic aeropropulsive aeroelastic vehicules, in Proceedings AIAA GNC conference, 1992

[31] J.F. Magni, Multimodel eigenstructure assignment in flight control design, Aerospace Science and Technology, volume 3, 1999

[32] J.M. Biannic, Commande robuste des systèmes à paramètres variables, PhD thesis, SUPAERO, France, 1996

[33] K. Seyffarth, M. Lacabanne, K Konig and H. Cassan, Comfort in turbulence for a large civil aircraft, Forum International Aéroélasticité et Dynamique de Structures, Strasbourg, France, 1993

[34] D. Alazard, A. Bucharles, G. Ferreres, J.F. Magni, S. Prudhomme, Towards a global methodology for flexible aircraft control design, ONERA-DLR Aerospace Symposium, Paris, France, 1999

[35] C. Doll, G. Ferreres, J. F. Magni, μ-Tools for Flight Control Robustness Assessment, Aerospace Science and Technology (Special Issue : flight control law design), 1998

[36] G. Ferreres, J.M. Biannic, A μ analysis technique without frequency gridding, American Control Conference, 1998